

Introduction: The initial accretion of primitive asteroids (meteorite parent bodies) from freely-floating nebula particles remains problematic. Traditional growth-by-sticking models in *turbulent* nebulae encounter a formidable “meter-size barrier” due to both drift and destruction, or even a mm-to-cm-size “bouncing” barrier [1]. Even if growth by sticking could somehow breach these barriers (perhaps if the actual sticking or strength is larger than current estimates, which are based on pure ice or pure silicate), turbulent nebulae present further obstacles through the 1-10km size range [2]. On the other hand, *nonturbulent* nebulae form large asteroids too quickly to explain long spreads in formation times, or the dearth of melted asteroids [1]. Thus, the intensity of nebula turbulence (or “ α ”) is critical to the entire process. Theoretical understanding of nebula turbulence continues to evolve; while recent models of MRI (magnetically-driven) turbulence favor low-or-no-turbulence environments [3], purely hydrodynamic turbulence is making a comeback with three recently discovered mechanisms generating turbulence of moderate α which do not rely on magnetic fields at all [4-7].

Leapfrog models and planetesimal “IMFs”: An important observational clue regarding planetesimal formation is an apparent 100km diameter peak in the pre-depletion, pre-erosion mass distribution of asteroids [8]; we call direct transformations of small nebula particles into large objects of this size, which avoid the problematic m-km size range, “leapfrog” scenarios (for a recent review see [1]). Unfortunately, new models show that “lucky” particles (the largest particles at the tail of the size distribution, that grow by sticking somewhat beyond the nominal fragmentation and drift barriers) are far too rare to trigger leapfrog processes such as gravitational “streaming” instabilities (SI) alone [9], under conditions of weak-to-moderate nebula turbulence. We found recently that another leapfrog hypothesis (turbulent concentration or TC alone) also fails to produce 100km planetesimals unless its building blocks are considerably larger (several cm to dm radius) than individual chondrules [10,11]. We suggested that a combination of TC and SI working together - a “Clustering Instability” or CI (this could be thought of as a triggered or nonlinear instability) - might lead to the observed planetesimal IMF under conditions of moderate turbulence [10,11].

The cm-dm nebula particle sizes upon which this process acts must reflect aggregates containing $10^4 - 10^5$ or more chondrule-size particles. However, model aggregates of dust-rimmed, chondrule-sized particles only grow to some mm-cm in radius, assuming sticking and strength properties of pure silicates [12]. Thus, growth by sticking must be slightly more robust than is generally accepted if cm-dm aggregates are to grow. It may be that “sticky” organics or frost on the rims of particles might aid in sticking. We suggested that some effort be devoted to searching for *aggregates* of chondrules that might have grown and remained together in the nebula, wandering around for some time before being accreted by a process such as the hypothetical CI [10,11].

NWA5717: evidence for chondrule aggregates? This

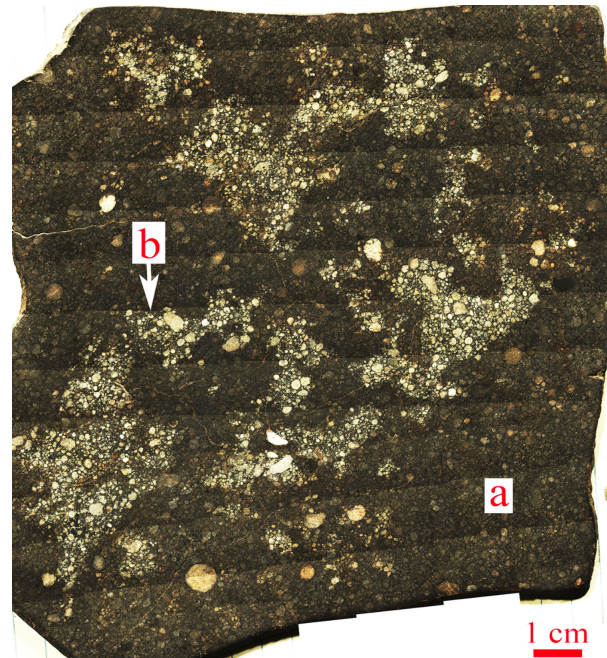


Figure 1: A 13x15 cm section of NWA5717 [14], a different slab from the same meteorite analyzed by [13] who first described the two different lithologies (a) and (b). We suggest the light clumps (b) may be surviving *aggregates of chondrules* whose chemical and isotopic properties are very different from those in similar aggregates (not so easily distinguished) of the more plentiful dark material (a). Our hypothesis is that chondrules of like properties formed and aggregated by sticking in regions of different chemical and isotopic composition, before the aggregates were mixed together into some region where they were incorporated into a parent body, perhaps by a “leapfrog” process [10,11]. Further study of this chondrite and others like it may show (or preclude) that chondrules can grow by sticking into clusters several cm across, larger than now generally expected.

fascinating UOC (figure 1) is of petrologic type 3.05 [13,14]. It contains two lithologies, denoted “dark” (a, apparently the host) and “bright” (b, the inclusions). Although [13] say the chondrite is from the “fragmental regolith” of some parent body, the lithologies do not have clastic or fragmental boundaries and the sample overall appears to be seamlessly “primary” in texture. The boundaries between the two lithologies are not always sharp, with evidence for alteration sometimes crossing or cutting individual chondrules. Sometimes, isolated single (a) chondrules can appear within (b) lithologies. The chondrule sizes in the two lithologies are the same [13,14].

However, the major element chemistry and oxygen isotope compositions of the chondrules within the the two lithologies (specifically the chondrules *per se* but not their fine-grained rims) are significantly different [13,14]. There is evidence for only minor terrestrial weathering [13], but the difference in O-isotopes is very significant ($\Delta^{17}\text{O} = 0.5(\text{a})$ vs. $0.07(\text{b})$). This

difference might be nebular in origin, or might be explained by mild parent body aqueous alteration (the more altered “dark” lithology is isotopically “heavier”). For this to be the case, it would require a very small amount of “heavy” water ice to have been localized in the dark lithology (a) and absent from the “light” lithology. A quantitative assessment of this possibility has not yet been done. Even more significant perhaps is the very different Mg/Fe ratio in the chondrule cores (but not rims) between the dark lithology (Fa10-20) and the light lithology (Fa < 3) [13]. Neither of the lithologies resembles common chondrite groups, but they do bear some resemblance to other ungrouped, metal-poor chondrites [13].

Collisional growth of aggregates: The physics of collision rates and outcomes involves the so-called “kernel” $K = n^2(r)\pi r^2 v_{rel}(r)$, where r is the particle radius, n is its local volume density, and $v_{rel}(r)$ is a typical relative velocity at collision. Some typical global average n and $v_{rel}(r)$ are usually adopted [9,15] which neglect subtle effects of particle clustering in turbulence. Yet, the theory of turbulent concentration (TC; [1,16]) already anticipates that the particle density can vary strongly from place to place because of the way particles of different size respond to turbulence, and the collision velocity does too. One can ratio the “observed” kernel from very large numerical simulations to the “naive” kernel which accounts for none of these effects, and separate the ratio into a local concentration term $g(r)$ (the Radial Distribution Function), and the ratio $v_{rel}(r)/u_\eta$ (where u_η is the velocity on the smallest scale of the turbulence - the Kolmogorov scale η).

Two recent and relevant studies [17,18] both show significant (order of magnitude or more) increases in the $g(r)$ term as the spatial scale decreases to the collision scale of chondrules, showing that a given chondrule-size particle is embedded in a local density much higher than “average”. However, there is some disagreement about whether and how much the companion term $v_{rel}(r)$ decreases to small scales. Thus, predicting collision kernels in the nebula for particles with radius $r \ll \eta$ quantitatively is not easy or well understood. Current studies have been done at low Reynolds Number Re (or turbulent intensity) and spatial scales far larger than the collisional (particle size) scale. It does seem [17,18] that relative velocities at collision are significantly lower (by a factor of *at least* several) than the current estimates, making sticking easier and forestalling bouncing, thus allowing growth of aggregates to larger sizes than as modeled by, eg, [9] or [15]. On one hand [17], increasing volume densities (through $g(r)$) might overcome decreasing velocities and the kernel might be orders of magnitude larger than currently expected, with a very sharp preference for equal-sized particles having stopping time t_s comparable to the Kolmogorov eddy time t_η , or Stokes number $St = t_s/t_\eta = 1$. On the other hand [18], the decreasing velocity may exactly cancel the increasing density, leaving the kernel and collision rates close to current estimates, but still with very low relative velocities that significantly favor sticking over bouncing. The outcomes would be different in detail, but both tend to support growth to larger aggregates than in current models [9,12]. This conclusion would be consistent with the suggestion that the light colored lithologies of figure 1 are indeed large ($10^5 - 10^6$ chondrule) aggregates. Both [17,18] find that collision rates between particles which have $St < 1$, are lower by St to some power; that is, particles aerodynamically selected for high collision rates and high sticking

coefficients are likely to be those with $St \sim 1$ (estimated at roughly chondrule size in the asteroid belt region by [19]).

Chondrule size distributions can help us understand these aerodynamic effects. It was thought by [19] that chondrule size distributions were quite narrow, and that this was in agreement with direct TC into self-gravitating assemblages that quickly became planetesimals. More recently and almost simultaneously, new observations of chondrule size distributions in Allende [20,21] showed the size distribution to be much broader than previously thought, *and* new models suggested collisional growth to the cm-dm scale, resulting in a broader size distribution [10,11]. The most recent observations of NWA5717 [14] show size distributions having good agreement in shape, if not in mean size, with those in Allende [20,21].

Cometary aggregates: An unrelated observation may be relevant in this regard. It has been shown [22] that in cometary aggregate IDPs and Wild 2 aggregate particles, the silicate and sulfide monomers (which have very different densities) have equal radius-density product within each aggregate. On the face of it, this is highly suggestive of aerodynamic sorting (see [23] for other examples). However the monomer grains involved are 0.03-0.2 μm in radius, and nominal nebula gas densities and turbulent α in the outer solar system suggest that such particles would have $St \ll 1$, making it very hard for them to grow by collisional sticking with others of the same St (by the Kernel behavior described above). The paradox could be resolved if the local gas density in the regions where cometary aggregates formed were one or two orders of magnitude smaller than canonical model predictions, or the nebula α were one or two orders of magnitude higher, or some combination. These submicron grain monomers would then play the role of “chondrules” in those rarified regions, forming aggregates by collisions. Moreover, if this situation *were* the case, the *aggregates* made up from these monomers, which are tens to hundreds of times larger than the monomers, would become the analog of the chondrule aggregates in the light lithology of figure 1, and could for the same reason have a large enough St to be concentrated by TC (or CI) directly into planetesimals.

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